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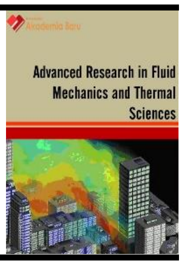

Jeffrey Fluid Embedded with Dust Particles over a Shrinking Sheet: A Numerical Investigation

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ABSTRACT

This study examines the flow behaviour of Jeffrey fluid together with uniform distribution of dust particles that moves over the vertical shrinking sheet. This intriguing mixture employs the two-phase model which mathematically describes the characteristic of both fluid and solid particles in a flow system by a set of partial differential equations. A convenient form of these equations is expressed in the form of ordinary differential equations through the use of similarity transformation and can subsequently be solved by applying the Keller-box method. Numerical solutions for several influencing parameters, namely suction, fluid-particle interaction, magnetic field and aligned angle on the flow and temperature fields of the two components (fluid and dust particles) are presented in graph form. In addition, the results of skin friction coefficient and Nusselt number at surface of sheet are summarized in the table and analysed in details. It is found that, the velocity and temperature profiles of fluid and dust phases show a similar behaviour in response to all involved parameters except for fluid-particle interaction parameter, respectively.

Keywords:
Two-phase flow; Dusty Jeffrey fluid; Shrinking sheet; Aligned magnetic field

1. Introduction

The study of boundary layer flow and heat transfer over a continuously moving surface has been motivated due to the increasing applications in manufacturing industry [1-2]. Few examples of such productions that frequently encountered in our daily life include glass blowing, hot rolling, polymer, metal sheet, wire drawing, cooling of a large metallic plate in a bath and spinning of fibers. In connection to this, the theoretical investigations on the flow problem of fluid induced by stretching and shrinking sheets under dissimilar conditions have been expanded in literature vastly. Sakiadis [3]

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examined the boundary layer flow of Newtonian fluid on a moving stretching surface at a constant velocity in a quiescent fluid. Later, Tsou *et al.,* [4] verified his obtained results experimentally and also conducted the heat transfer analysis for this flow case. Further, Crane [5] studied the two-dimensional flow and convective heat transfer that is generated entirely by the motion of stretching sheet and additionally, presenting the exact solution for both distributions. As continuance of these pioneer studies, several works are concerned with the temperature and mass fields in various circumstances [6-7]. On the other hand, Miklavčič and Wang [8] considered a steady flow of Newtonian fluid subjected to shrinking sheet in the presence of suction by providing both exact and numerical solutions. In the problem formulation, fluid is assumed to be sucked toward slot with a uniform velocity and they found that suction rate determines the uniqueness of solution, which is certainly different with stretching sheet case. Since then, exploration into flow characteristic of fluid associated with shrinking sheet has engaged the attention of numerous researchers, for instance Fang *et al.,* [9], Roşca and Pop [10], Bakar *et al.,* [11] and recently, Ghosh and Mukhopadhyay [12] have studied problems of shrinking flow by highlighting the slip effect on velocity and thermal distributions in Newtonian fluid and nanofluids.

The studies mentioned above are, nevertheless, focusing on the single-phase model and investigating flow behaviour of fluid only across stretching and shrinking surfaces. In fact, those works dismissed the notion of considering other components such as solid particles in a fluid system that may have a significant bearing on natural properties of fluid. Siddiqa *et al.,* [13] solved the free convection flow of Newtonian fluid with suspensions of solid particles over a vertical stretching sheet. In continuation to this study, Isa *et al.,* [14] presented numerical solution of dusty Newtonian fluid flow through a horizontal stretching sheet with the impact of hydromagnetic field. Meanwhile, Naramgari and Sulochana [15] and Makinde *et al.,* [16] conducted a numerical study on dusty non-Newtonian fluid, which is dusty nanofluid and dusty Williamson fluid, respectively. Moreover, research activities on the flow of Newtonian or non-Newtonian fluids containing dust particles (solid particles) are undergoing rapid development and most of them belong to stretching surface flow case, such as reported in [17-18]. Nonetheless, there is limited existing study into the two-phase flow that accounts for shrinking surface. In recent years, Hamid *et al.,* [19] carried out stability analysis on dusty fluid while Santhosh and Raju [20] took into account the unsteady flow of dusty Carreau-Casson fluids over shrinking sheet. Very recently the investigation related to the non-Newtonian dusty fluid over a stretching sheet has been continued by Dasman *et al.,* [21], Arifin *et al.,* [22] and Aljabali *et al.,* [23].

Motivated by the previous studies, the present work aims to investigate dusty Jeffrey fluid flow with combined effect of inclined magnetic field and suction across a vertical shrinking sheet. Numerical solutions provided here, are expected to expose the behaviour of both Jeffrey fluid and dust particles with the assistance of Keller-box method in solving the mathematical model for this current problem.

2. Problem Formulation

The purpose of the present study is to analyse the behaviour of boundary layer flow of an electrically conducting and incompressible Jeffrey fluid embedded with dust particles over a shrinking sheet in the presence of aligned magnetic field. The applied magnetics in this problem is different with the conventional magnetic since it happened to affect the flow with different angle. However, the transverse magnetic field is acting at fixed tranversed to the flow field. Furthermore, the conditions of suction and Newtonian heating (NH) boundary condition on velocity and thermal distribution are assumed at the surface of sheet, respectively. Figure 1 illustrates the physical configuration for the current investigation, where $x-$axis belongs to shrinking surface and $y-$axis is directed perpendicular to the sheet. It is also assumed that the shrinking sheet moves with the uniform velocity, $u_w(x)=-ax$ and the dust particles are considered to be in spherical shape, identical size and non-interacting.

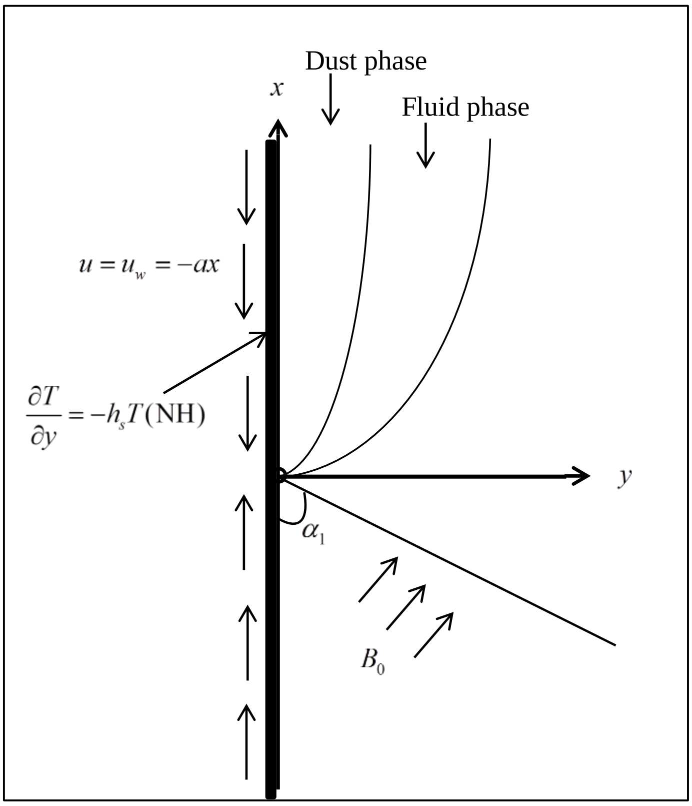

Fig. 1. Flow configuration of dusty Jeffrey fluid and coordinate system

To investigate the problem stated above, we consider that the governing boundary layer equations for dusty Jeffrey fluid can be represented by Siddiqa *et al.,* [13] and Kasim *et al.,* [18].
Fluid phase:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\nu}{1+\lambda_2}\left[\frac{\partial^2 u}{\partial y^2}+\lambda_1\left(u\frac{\partial^3 u}{\partial x\partial y^2}+v\frac{\partial^3 u}{\partial y^3}-\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2}+\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}\right)\right]+\frac{\rho_p}{\rho\tau_v}(u_p-u)$$
$$-\frac{\sigma u{B_0}^2}{\rho}\sin^2\alpha_1, \tag{2}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{\rho_p c_s}{\gamma_T}(T_p-T), \tag{3}$$

Dust phase:

$$\frac{\partial u_p}{\partial x}+\frac{\partial v_p}{\partial y}=0, \tag{4}$$

$$\rho_p\left(u_p\frac{\partial u_p}{\partial x}+v_p\frac{\partial u_p}{\partial y}\right)=\frac{\rho_p}{\tau_v}(u-u_p), \tag{5}$$

$$\rho_p c_s\left(u_p\frac{\partial T_p}{\partial x}+v_p\frac{\partial T_p}{\partial y}\right)=-\frac{\rho_p c_s}{\gamma_T}(T_p-T) \tag{6}$$

Note that, the physical quantities for fluid phase involved in the above equations are (u,v), μ, ρ, α_1, c_p, T and B_0, which correspond to the velocities components along x and y axes, coefficient of viscosity, density, aligned angle, specific heat, temperature and magnetic field strength. For dust phase, (u_p,v_p), ρ_p, $\tau_v=1/k$ with k is the Stoke's resistance (drag force), c_s, T_p and γ_T are correspondingly defined as the velocities components along x and y axes, density, relaxation time, specific heat, temperature and thermal relaxation time. Eq. (1)-(6) are accompanied by the following boundary conditions

$$u=u_w(x)=-ax,\ \ v=v_w,\ \ \frac{\partial T}{\partial y}=-h_s T \quad \text{at } y=0$$

$$u\to 0,\ \ u_p\to 0,\ \ v_p\to v,\ \ T\to T_\infty,\ \ T_p\to T_\infty \quad \text{as } y\to\infty \tag{7}$$

Here, a is positive constant and h_s is heat transfer parameter. Further, the similarity transformation for both phases are introduced as

$$\begin{aligned} &u=axf'(\eta),\ \ v=-(av)^{1/2}f(\eta),\ \ \eta=\left(\frac{a}{v}\right)^{1/2}y,\ \ \theta(\eta)=\frac{T-T_\infty}{T_\infty} \\ &u_p=axF'(\eta),\ \ v_p=-(av)^{1/2}F(\eta),\ \ \theta_p(\eta)=\frac{T_p-T_\infty}{T_\infty}, \end{aligned} \tag{8}$$

Upon using Eq. (8), the ordinary differential equations of Eq. (1)-(6) become

$$f'''+(1+\lambda_2)\left(ff''-f'^2\right)+De\left(f''^2-ff^{(4)}\right)+(1+\lambda_2)\beta N\left(F'-f'\right)-(1+\lambda_2)M\sin^2\alpha_1 f'=0, \tag{9}$$

$$\theta''+\Pr f\theta'+\frac{2}{3}\beta N\left(\theta_p-\theta\right)=0, \tag{10}$$

$$F'^2-FF''+\beta\left(F'-f'\right)=0, \tag{11}$$

$$\theta_p{}'F+\frac{2}{3}\frac{\beta}{\Pr\gamma}\left(\theta-\theta_p\right)=0 \tag{12}$$

and, boundary conditions in Eq. (7) can be written as

$$f(0)=S,\ f'(0)=1,\ \theta'(0)=-b\left(1+\theta(0)\right)\quad \text{at } \eta=0$$

$$f'(\eta)\to 0,\ f''(\eta)\to 0,\ F'(\eta)\to 0,\ F(\eta)\to f(\eta),\ \theta(\eta)\to 0,\ \theta_p(\eta)\to 0\quad \text{as } \eta\to\infty \tag{13}$$

where a prime ($'$) denotes differentiation with respect to η. Several physical parameters of suction, S, Deborah number, De, ratio of relaxation to retardation times, λ_2, magnetic field, M, mass concentration of particle phase, N, fluid-particle interaction parameter, β, Prandtl number, $\Pr$, specific heat ratio of mixture, γ, conjugate parameter for NH, b that are considered in Eq. (9)-(13) can be defined as follows

$$S=-\frac{v_w}{\sqrt{\upsilon a}},De=\lambda_1 a,M=\frac{\sigma B_0^2}{\rho a},N=\frac{\rho_p}{\rho},\beta=\frac{1}{a\tau_v},\Pr=\frac{\mu c_p}{k},\gamma=\frac{c_s}{c_p},b=-h_s\left(\frac{\upsilon}{a}\right)^{1/2} \tag{14}$$

It is worth to mention that, Eq. (9) can be reduced into the single phase flow of Jeffrey fluid without the presence of dust particles and magnetic field when $M=\alpha_1=\beta=N=0$ and $\gamma\to\infty$. Additionally, the exact solution for this limiting flow case, as mentioned by Roşca and Pop [10] take the following form

$$f(\eta)=S-\frac{1}{B}\left(1-\exp\left(-B\eta\right)\right), \tag{15}$$

where $B=\dfrac{S+\sqrt{S^2-4}}{2}$. Therefore, its second derivative results to

$$f''\left(0\right)=-\frac{1}{2}\left(S+\sqrt{S^2-4}\right) \tag{16}$$

Next, the skin friction coefficient C_f and the local Nusselt number Nu_x can be denoted as

$$C_f=\frac{\tau_w}{\rho U^2(x)},\qquad Nu_x=\frac{xq_w}{k(T_w-T_\infty)}, \tag{17}$$

where τ_w and q_w are respectively the rate of heat transfer and surface heat flux, given as

$$\tau_w=\frac{\mu}{1+\lambda_2}\left[\frac{\partial u}{\partial y}+\lambda_1\left(u\frac{\partial^2 u}{\partial x\partial y}+v\frac{\partial^2 u}{\partial y^2}\right)\right]_{y=0},\qquad q_w=-k\left(\frac{\partial T}{\partial y}\right)_{y=0} \tag{18}$$

with $\mu = \rho \nu$ and k, thermal conductivity. By using Eq. (8), both non-dimensional skin friction coefficient and Nusselt number can be written as

$$C_f \operatorname{Re}_x^{1/2} = \left(\frac{1+De}{1+\lambda_2}\right) f''(0), \qquad Nu_x \operatorname{Re}_x^{-1/2} = \gamma\left(1+\frac{1}{\theta(0)}\right). \tag{19}$$

where $\operatorname{Re}_x = (ax^2/\nu)$ is the Reynolds number.

3. Numerical Procedure

The system of ordinary differential equations in Eq. (9)-(12) is solved numerically under boundary conditions in Eq. (13) by using the Keller-box method, which employs the Matlab software as a tool for computing the equations. The important point to address is that, this method works on any order of non-linear differential equations and has been proven to be unconditionally stable. Furthermore, it can be considered perfectly compatible in solving the mathematical model presented herein if the current results agree reasonably well with the existing exact solutions. Thus, a direct comparison between both solutions has been performed. In the program, a uniform step size, $\Delta\eta = 0.01$ is selected and found to give accurate numerical results. Moreover, the finite boundary layer thickness, $\eta_\infty = 4$ and 1 are set up for velocity and temperature profiles, respectively which directly correspond to satisfy the condition of far away from the surface $(\eta \to \infty)$, as presented in equation in Eq. (13). It means that, both profiles need to approach zero at their free stream value.

4. Results and Discussion

In this section, the numerical results obtained for two-phase flow of dusty Jeffrey fluid has been discussed by varying the parameters involved, including suction, S, fluid-particle interaction, β, magnetic field, M, and aligned angle, α_1. Table 1 shows the comparison of single phase flow of Jeffrey fluid with analytical solution and also previous study reported by Roşca and Pop [10], who investigated the viscous fluid flow using bvp4c for several values of S. The values shown in the bracket are the relative errors, which implies to the ratio of magnitude value of discrepancy between an exact and numerical solutions with the exact ones. From the table, it can be seen that, the present results have a very small relative error and accordingly, the numerical solutions obtained from this study are considered accurate. The results displayed herein are computed by setting the fixed values of $\Pr = 10$, $De = 0.2$, $\lambda_2 = 0.4$, $S = M = 2$, $\alpha_1 = \pi/6$, $\beta = N = 0.5$, $b = 0.3$ and $\gamma = 0.1$.

Figure 2 and 3 illustrate the velocity profiles of fluid phase, $f'(\eta)$ and dust phase, $F'(\eta)$ for several values of suction, S. It can be seen from Figure 2 that the velocity profiles of both phases increase as the influence of S increases. This is due to the application of suction which physically accelerated the fluid motion towards the surface and in turn motivates the dust particles. However, in Figure 3, the results acquired suggest that the increasing value of S reduces the temperature profile of both phases and records a small variation in dust temperature when the value of S changed. Nevertheless, it is also found that the dust particles move closer to the surface as compared to the fluid phase.

Table 1
Comparison of $f''(0)$ for various values of S

S	Analytical Eq. (17)	Roşca and Pop [10]	Present
2.0	1.0000	1.0106 (1.06%)	0.9969 (0.31%)
2.5	2.0000	2.0000 (0%)	2.0000 (0%)
3.0	2.6180	2.6180 (0%)	2.6180 (0%)
3.5	3.1861	-	3.1861 (0%)
4.0	3.7321	-	3.7321 (0%)

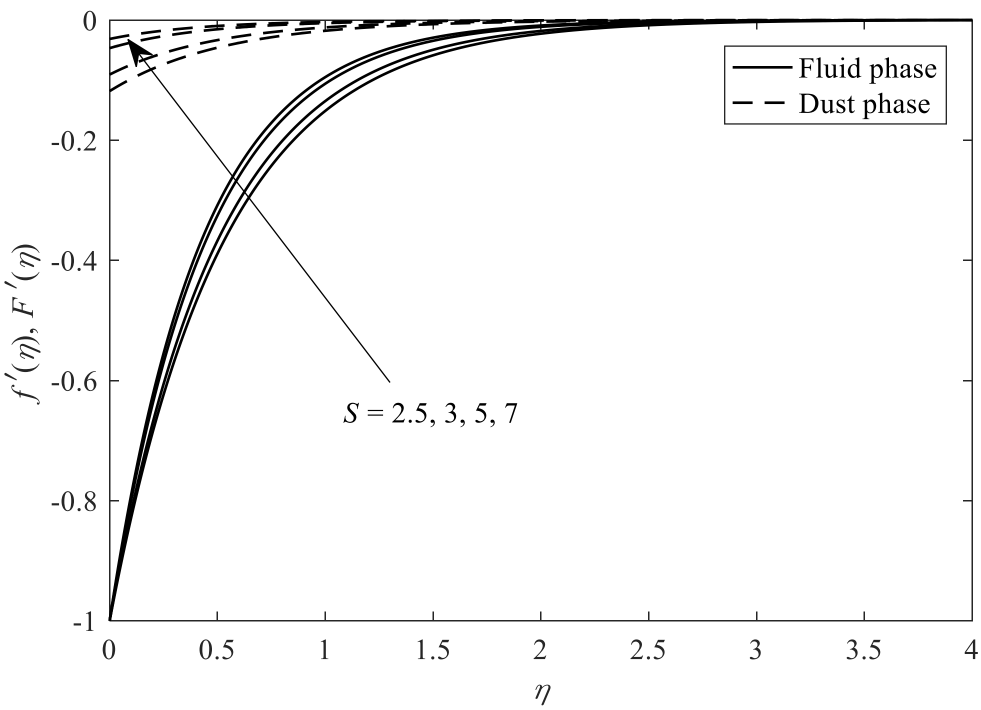

Fig. 2. Velocity profiles of fluid and dust phases for various values of S

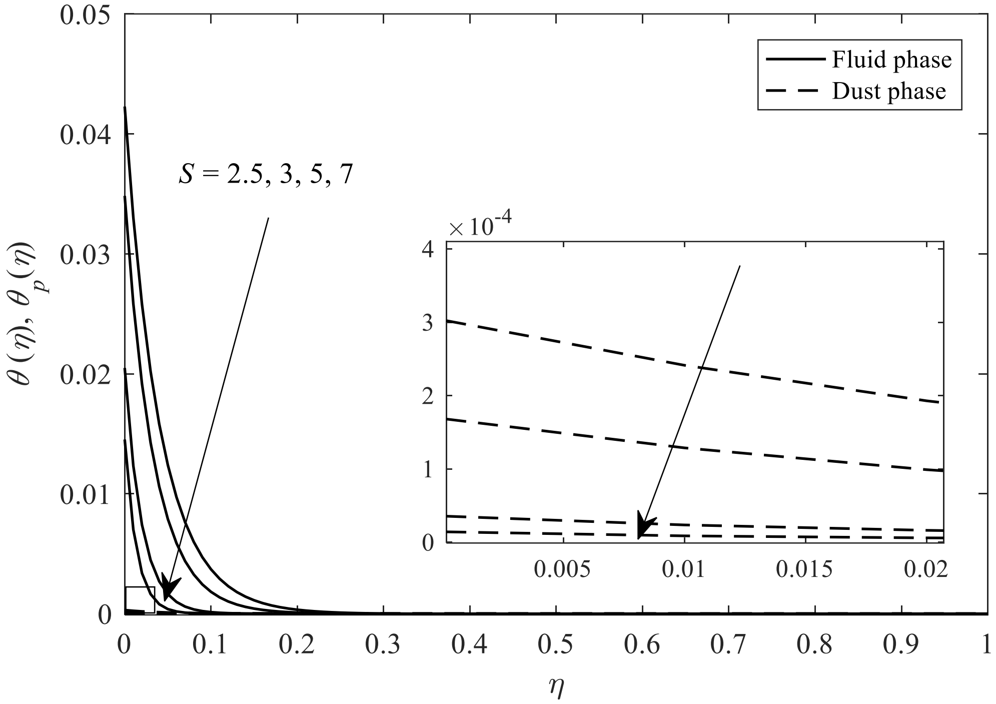

Fig. 3. Temperature profiles of fluid and dust phases for various values of S

Next, Figure 4 and 5 depict the effect of fluid-particle interaction parameter, β on velocity and temperature profiles of fluid and dust phases, respectively. From Figure 4, it is found that fluid velocity decreases as β increases and a reverse behaviour is noticed in dust velocity. But, a similar trend in temperature profile of both phases is observed as the value of β rises, as shown in Figure 5. A possible explanation for this phenomenon is that, by enhancing the value of β, the Jeffrey fluid has be driven to flow with low speed along the sheet since the velocity of relaxation time of dust particles, τ_v is increased. Therefore, dust particles move speedily by means of approaching the fluid velocity and as a result, it exerts a drag upon fluid when they came into contact at which the fluid becomes decelerated.

Figure 6 to 9 illustrate the variation of velocity and temperature of fluid and dust particles, respectively under the influence of magnetic field, M and aligned angle, α_1. It can be observed from those figures that, the impact of both parameters tends to have a similar tendency toward the flow and temperature distributions of fluid and dust phases. Specifically, as demonstrated in Figure 6 and 8, the increasing in values of M and α_1 accelerates the velocities of fluid and dust particles, which consequently decreases the momentum boundary layer thickness. Meanwhile, the temperature profiles of both phases decreased insignificantly by growing effects of M and α_1 as captured in Figure 7 and 9. Generally, an enhancement of magnetic field in the boundary layer flow motivates the Lorentz force that will reduce the velocity profile of fluid and dust phases, as reported by several researchers [18, 24-25]. Yet, an opposite result has been discovered in this study and it is worth mentioning that the present solutions portray the similar behaviour to those flow cases considered by Sandeep *et al.,* [26], who solved dusty nanofluid flow in the presence of magnetic field.

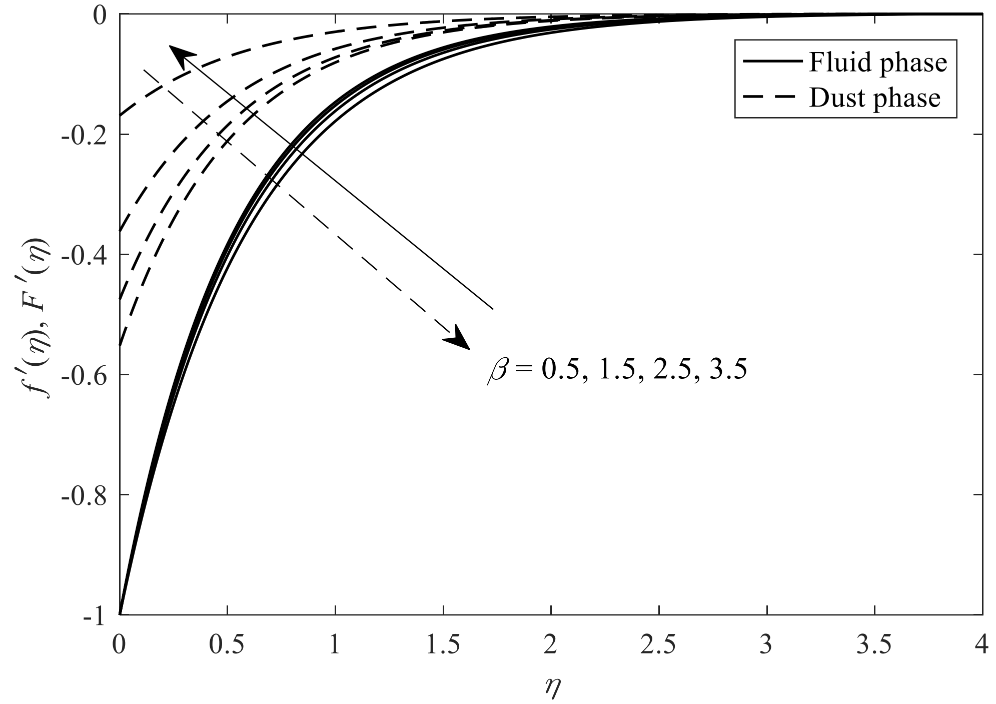

Fig. 4. Velocity profiles of fluid and dust phases for various values of β

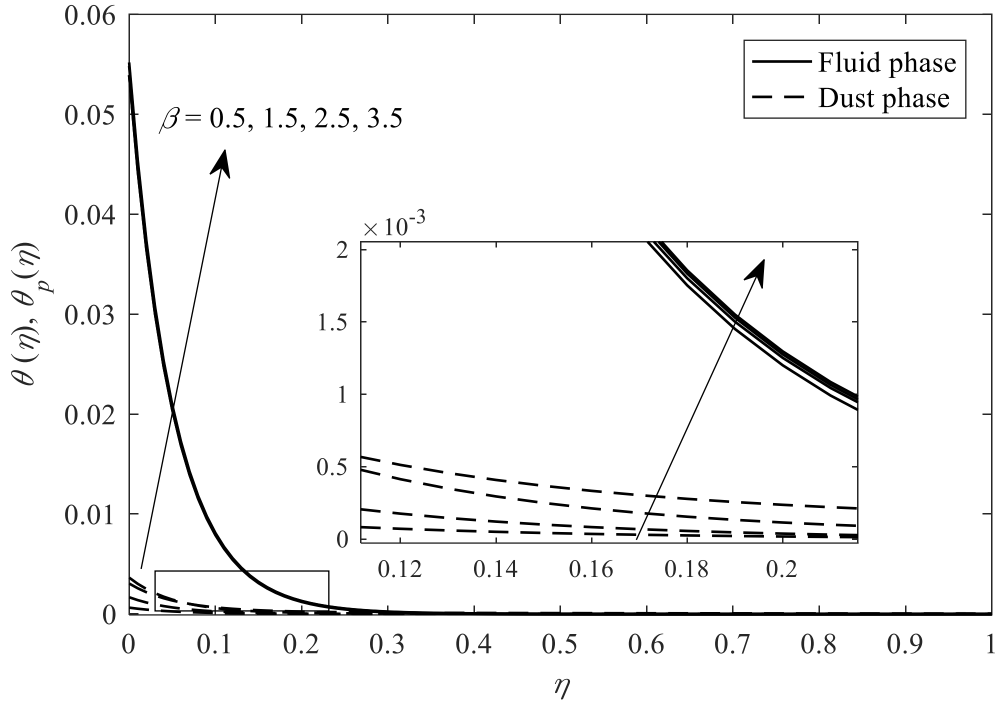

Fig. 5. Temperature profiles of fluid and dust phases for various values of β

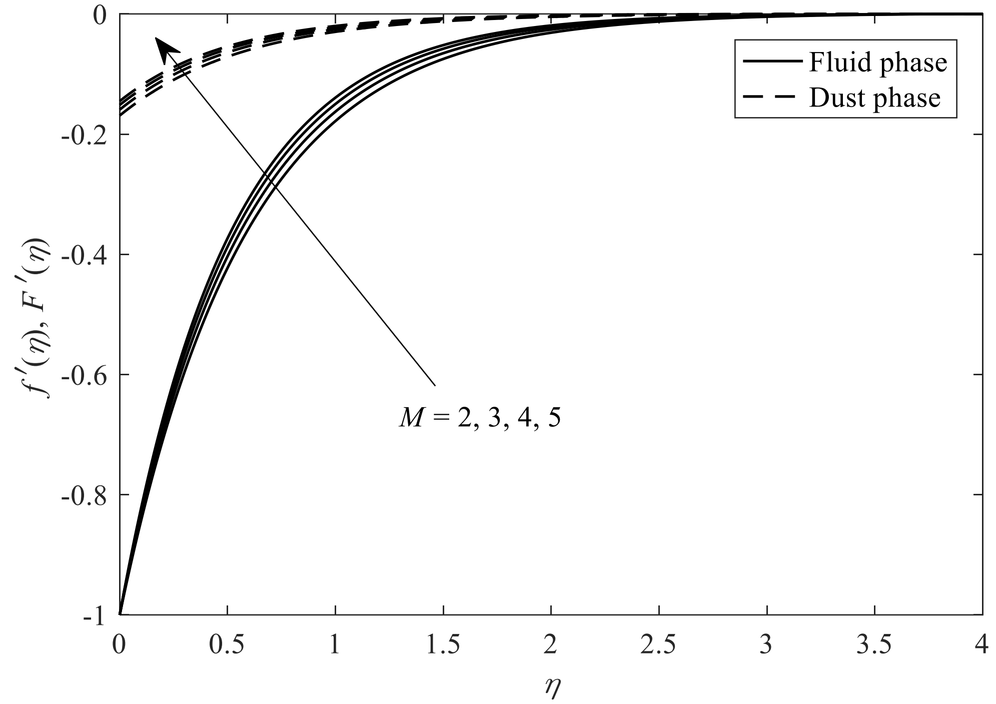

Fig. 6. Velocity profiles of fluid and dust phases for various values of M

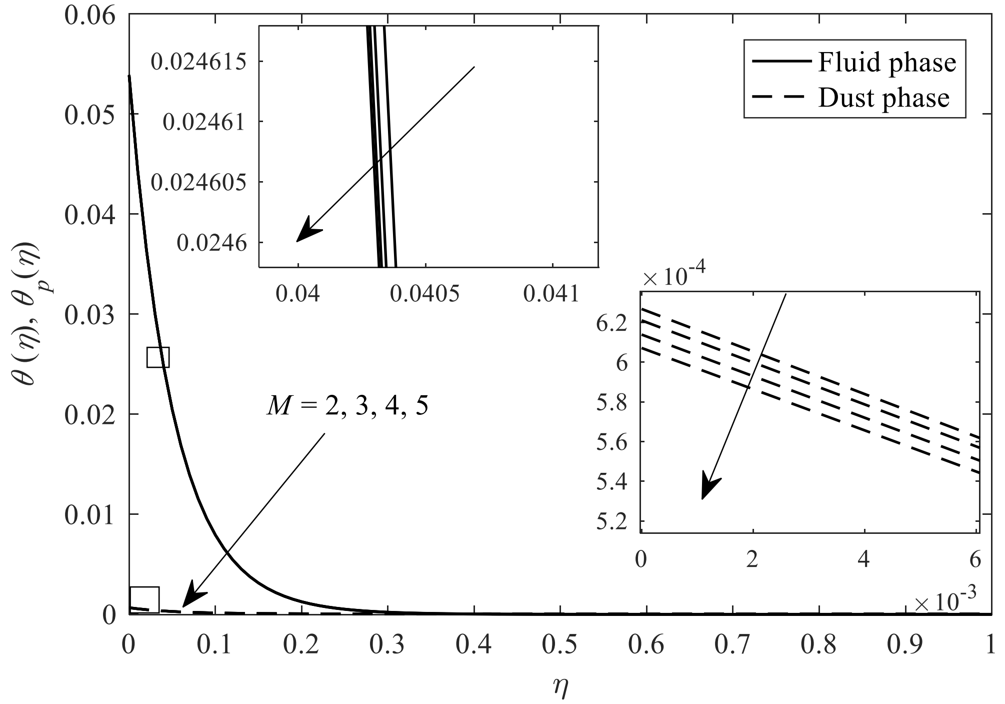

Fig. 7. Temperature profiles of fluid and dust phases for various values of M

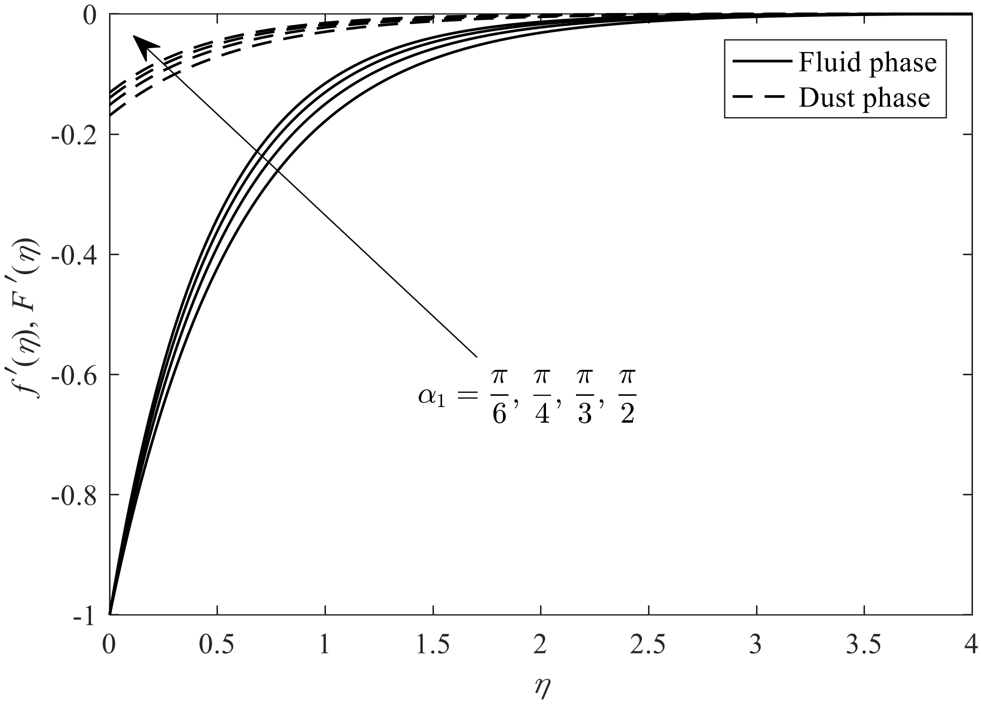

Fig. 8. Velocity profiles of fluid and dust phases for various values of α_1

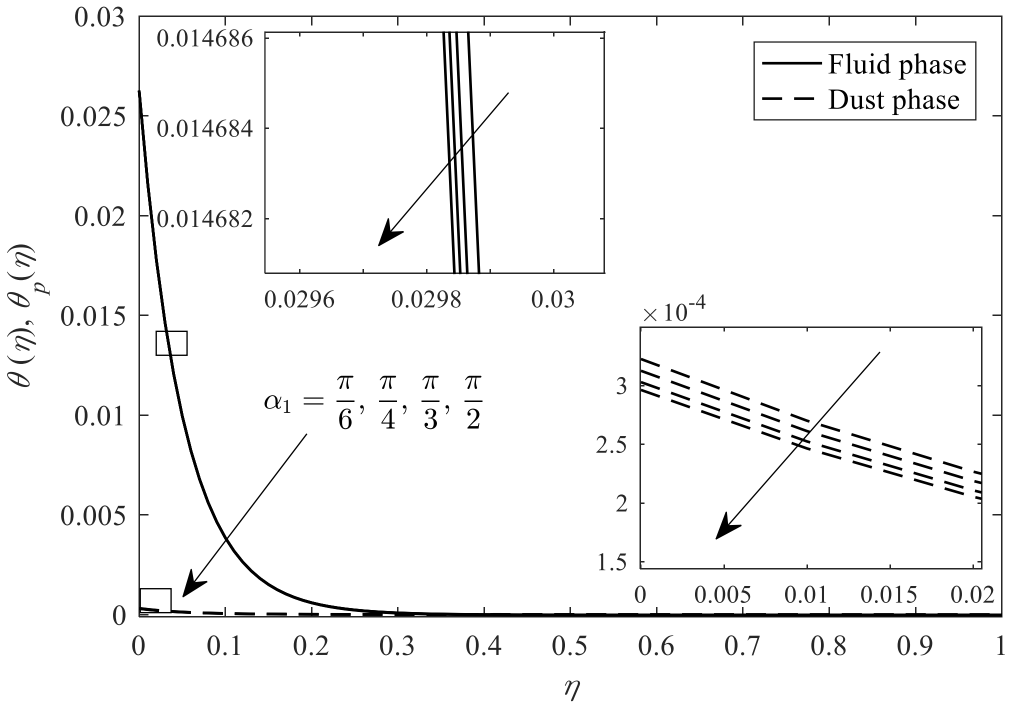

Fig. 9. Temperature profiles of fluid and dust phases for various values of α_1

Table 2 displays the numerical values of skin friction coefficient, $C_f\mathrm{Re}_x^{1/2}$ and Nusselt number, $Nu_x\mathrm{Re}_x^{-1/2}$ for several dimensionless parameters. It can be observed from the table that, the impacts of S and α_1 on the variation values of $C_f\mathrm{Re}_x^{1/2}$ and $Nu_x\mathrm{Re}_x^{-1/2}$ are qualitatively similar, in which an increasing trend is noticed. However, it is noticed that a reverse situation happens in responds to parameters β and M where the decreasing values of $Nu_x \mathrm{Re}_x^{-1/2}$ are initially observed and as both parameters are continued to increase, the increasing trend is detected. Meanwhile, for the respective parameters, the pattern in the variation value of $C_f \mathrm{Re}_x^{1/2}$ can be seen similar to the rest of parameters, which are S and α_1. This can be explained by the fact that, an enhancement in those physical parameters accelerates the fluid velocity as demonstrated in Figure 2, 4, 6 and 8. Thus, at the surface of the sheet, the shear stress raises which then increases the friction between fluid and surface. In addition, the values of $Nu_x \mathrm{Re}_x^{-1/2}$ is expected to decline as consequences of being inversely proportional to the surface temperature. It is also revealed the big value of M led to improve the skin friction coefficient but give very small changes to Nusselt number.

Table 2
Variation of $C_f \mathrm{Re}_x^{1/2}$ and $Nu_x \mathrm{Re}_x^{-1/2}$ for various values of S, β, M and α_1

S	β	M	α_1	$C_f \mathrm{Re}_x^{1/2}$	$Nu_x \mathrm{Re}_x^{-1/2}$
2	0.5	2	$\pi/6$	1.47655	19.54372
4				1.84510	39.76709
8				2.04860	79.88638
10				2.09115	99.91037
2	1	2	$\pi/6$	1.52597	19.56328
	3			1.62979	19.46213
	5			1.67935	19.61186
	10			1.73701	19.69645
2	0.5	2	$\pi/6$	1.47652	19.54372
		5		1.68912	19.54156
		10		1.94100	19.54563
		15		2.13404	19.54982
2	0.5	2	0	1.25969	19.32614
			$\pi/4$	1.62609	19.54148
			$\pi/3$	1.74676	19.54211
			$\pi/2$	1.84990	19.54379

4. Conclusion

This paper investigates the boundary layer flow of Jeffrey fluid containing a uniform distribution of spherical dust particles over a shrinking sheet under the effects of suction and aligned magnetic field. Therefore, the analysis is performed by considering four significant dimensionless parameters, which are S, β, M and α_1 on the flow and temperature profiles of fluid and dust phases, respectively. It is found that the behaviour displayed by dusty Jeffrey fluid as studied in this paper has the following important features:

i. Generally, the fluid temperature is higher compared to dust phase for all the evaluated parameters.
ii. The velocity profile of both fluid and dust phases increases with the increase in S, M and α_1, whereas an opposing behaviour is observed for temperature profile.
iii. The reverse effect on the velocity profile of fluid and dust phases is noticed due to the increase of β, while temperature profile shares the similar trend.

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